A SINGLE POINT PRESSURE APPROACH AS INPUT FOR INJURY MODELS WITH RESPECT TO COMPLEX BLAST LOADING CONDITIONS

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ABSTRACT

Blast injury models, like Axelsson and Stuhmiller, require four pressure signals as input. Those pressure signals must be acquired by a Blast Test Device (BTD) that has four pressure transducers placed in a horizontal plane at intervals of 90 degrees. This can be either in a physical test setup or in a numerical environment.

However, using a BTD for blast injury assessment can be very cost-inefficient since this procedure only predicts injury at one specific location. For injury predictions at other positions a new simulation or experiment must be performed. Several single point approaches remove the need for a BTD by using the free field pressure as model input. However, it is not clear whether these will give correct results.

To assess the applicability of these methods, case studies of different single point approaches have been performed for different charge weights, ranging from 9 to 5000 kg. Distances from the charges corresponded to free field lung injury threshold levels and 50% survivability levels. Results from the full BTD approach were compared with the single point methods. In particular, the influence of reflecting surfaces was studied.

INTRODUCTION

Determining the human injury that will be caused by a given explosion is a challenging problem. Explosions can cause injury in a number of ways, in particular through blast wave interaction and fragment impact. In this paper we will focus only on injuries due to blast waves.

The actual blast wave injury depends on many parameters like the size and composition of the bomb, the location of the human relative to the bomb, the geometry of the surrounding area etc. Further, the exact injury mechanisms in humans are not completely understood. As a consequence, it is very difficult to solve the problem analytically. A direct experimental approach to determine injury on humans is obviously not possible either.

Bowen [1] performed various animal experiments to determine the survival probability for subjects exposed to a free field blast wave. This resulted in a number of curves expressing the probability of survival as a function of maximum pressure and blast wave duration. After scaling, it was thought that the results would be applicable to humans as

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well. Later, Bass [2] has included more data in the analysis to produce updated survival curves.

However, these formulas have several limitations. First, they assume a free field blast wave and are therefore not applicable to complex blast waves that develop in a situation where the initial wave can reflect against several walls. Secondly, they only consider lethality and not injury risk. Finally, Bowen and Bass focused on lethality from lung injuries and neglected injuries to other body parts, such as the thorax and abdominal area.

Axelsson [3] addressed these problems by creating a mathematical model which could take input data generated by a blast wave of any shape and provide an injury prediction for a person exposed to this wave. Besides lung injury, the Axelsson model also accounts for injuries to the respiratory tract, the thorax and the abdominal area. (Stuhmiller [4] has developed a similar mathematical model, but since the actual model is not public, it will not be studied further here).

Unfortunately, it is not the single point field pressure which is input to the Axelsson model. Instead the model requires four pressure histories acquired by pressure transducers placed on a cylindrical Blast Test Device (BTD). These pressures can be determined either in a physical test setup or in a numerical environment. The BTD procedure complicates things considerably since each experiment or simulation can only predict injury at the BTD location. To determine the injury risk as a function of position in a larger area therefore requires a huge number of experiments or simulations.

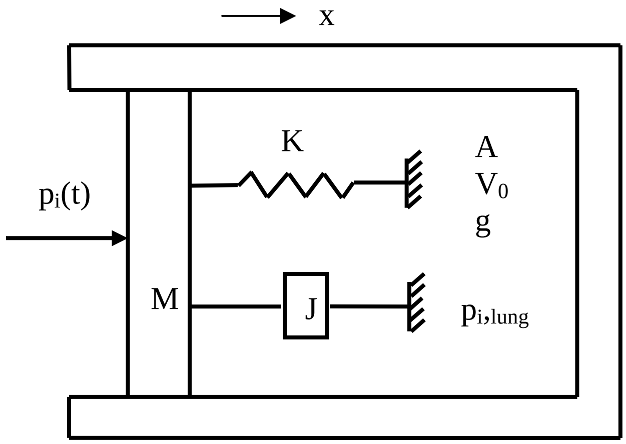
To get around this problem, various options for "single point approaches" are studied in this paper. One way is to use the Axelsson model without the BTD, but with the field pressure as input. Secondly, Li [5] suggested the Weathervane model which uses the field pressure at a given location to estimate what the pressure would have been at the four gauges if a BTD had been present. Finally, TNO [6] has developed an approximation procedure of the Axelsson model which is thought appropriate for a single point approach.

If any of these single point methods produce injury estimates that are reasonably accurate compared with the Axelsson BTD model, they would considerably simplify calculations of expected injury in a complicated geometry. In this paper we will investigate the accuracy of the single point approaches by performing numerical simulations for a wide range of blast scenarios and comparing the injury estimates of the various methods with the Axelsson BTD approach. (Whether the Axelsson BTD model actually provides injury estimates that are physically correct, is a completely different issue, and will not be discussed in this paper.)

AXELSSON BTD MODEL

The Axelsson BTD model is a single degree of freedom (SDOF) system meant to describe the chest wall response of a human exposed to a given blast wave (Figure 1). To predict the blast injury, the model requires pressure data from four transducers located at

90 degrees interval around a Blast Test Device (BTD) (Figure 2), exposed to the relevant blast wave.



Name	Explanation
A	Effective area
M	Effective mass
V_0	Lung gas volume at x=0
J	Damping factor
K	Spring constant
p_0	Ambient pressure
$p_i(t)$	External (blast) loading pressure
$p_{i,lung}(t)$	Lung pressure
g	Polytropic exponent for gas in lungs
x	Chest wall displacement

Figure 1: Mathematical model of the thorax according to Axelsson [3]

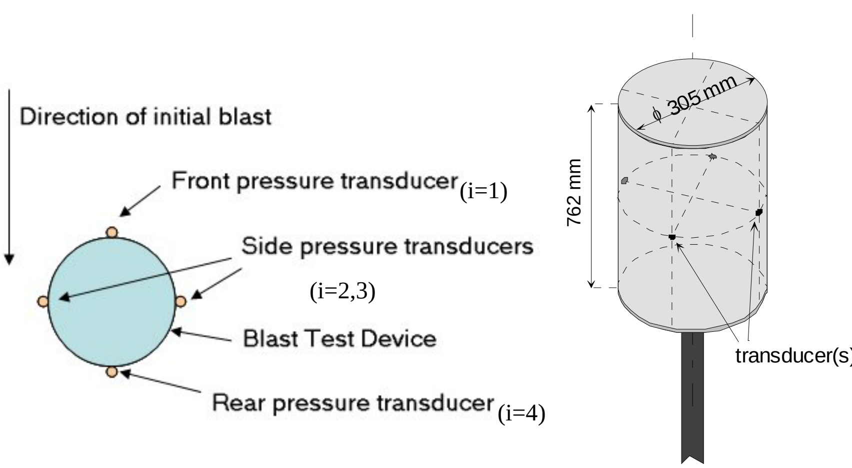


Figure 2: Blast Test Device [3]

The mathematical formulas for the Axelsson BTD model are expressed by four independent differential equations:

$$M \cdot \frac{d^2 x_i}{dt^2} + J \cdot \frac{dx_i}{dt} + K \cdot x_i = A \cdot \left[p_i(t) - p_{i,lung}(t) \right] \qquad i = 1, 2, 3, 4$$

$$p_{i,lung}(t) = p_0 \left(\frac{V_0}{V_0 - A \cdot x_i} \right)^g \tag{1}$$

The values of the model parameters are given in Axelsson's original article [3]. Input to the model are the four $p_i(t)$ pressure histories measured on the BTD. With this input, the differential equations can be solved for chest wall positions $x_i(t)$ and chest wall velocities $v_i(t) = \frac{dx_i}{dt}(t)$.

This enables calculation of a quantity called the Chest Wall Velocity Predictor (V) according to the following equation:

$$V = \frac{1}{4}\sum_{i=1}^{4} \max\left(v_i(t)\right) \tag{2}$$

From small charge experiments with sheep in closed containers, Axelsson was able to correlate V with injury level for internal organs (ASII) through curve fitting:

$$ASII = (0.124 + 0.117V)^{2.63} \tag{3}$$

SINGLE-POINT MODELS

The need for a BTD in every location means that the Axelsson model is not so convenient for calculations (or experiments) of the injury level as a function of position in a large area. In this paper we will look at several methods for simplifying the procedure:

Axelsson SP model

The Axelsson SP model is just the Axelsson model without the BTD, but using the single point (SP) field pressure (i.e non-BTD) in the given location as input to the Axelsson differential equations. The four differential equations are then identical, so that $V = \max(v_1)$. This is not the way Axelsson intended for the model to be used, but it is still worth looking at what kind of results can be obtained.

Weathervane SP model

The Weathervane SP model is a more sophisticated approach by Li et.al [5]. Instead of ignoring the BTD, this model tries, based on the field pressure, to estimate what the pressure would have been for the four sensors if a BTD had been present. One of the pressure sensors is always assumed to face directly towards the blast wave and the procedure is then as follows:

Sensor facing blast wave $p_1(t)$: Maximum pressure and total impulse are assumed equal to the reflected blast load on a rigid infinite wall. These values can easily be found analytically. The full pressure history $p_1(t)$ is then found by assuming a Friedlander form for the pressure wave and iterating the decay parameter until the total reflected impulse is correct (as calculated by ConWep [7]).

Side sensors $p_2(t)$ and $p_3(t)$: Assumed equal to the field (side-on) pressure. (Same as the pressure input in the Axelsson SP model).

Rear sensor $p_4(t)$: Assumed equal to the ambient pressure p_0.

These pressure histories are then used in the Axelsson BTD model for calculation of the chest wall velocity predictor *V*.

Modified Weathervane SP model

A problem with the Weathervane model is that finding the front pressure $p_1(t)$ is not straightforward, but involves a cumbersome iteration process to find the correct impulse. For implementation in a hydrocode this is inconvenient. To get around this, an alternative approach is possible, where the Friedlander waveform is not used, but instead the estimated sensor pressure $p_1(t)$ is assumed equal to the reflected pressure at each point in time. This will be called the Modified Weathervane model. The difference from the regular Weathervane model is not very big, but in general the Modified Weathervane will give slightly longer pulses and consequently slightly higher estimates for the chest wall velocity predictor.

TNO SP model

TNO has developed an approximation procedure of the Axelsson BTD model. The method is fully described in [6]. Instead of solving the four differential equations (1), the Axelsson chest wall velocity predictor *V* is estimated from the main blast characteristics: peak pressures, the impulses, and the points in time of the different peaks (see Figure 3). An exact pressure-time curve is not necessary. The field (side-on) blast wave has been chosen as pressure input in this first exploration of the TNO SP method and its possibilities.

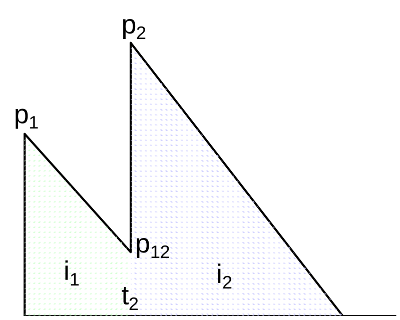


Figure 3: Relevant characteristics of an arbitrary shock wave with two peaks, used for the approximation procedure of TNO [6]

SCENARIOS

In this paper we will investigate whether the various single point models are good approximations of the Axelsson BTD model. Of special interest is how they compare in complex blast situations, more particularly close to a wall. The comparison will be done by performing numerical simulations for a wide range of relevant cases.

A sketch of the simulation set-up is shown in Figure 4. In general the Axelsson BTD simulations consist of a BTD at different distances x_2^j from a wall. To investigate both

short and long blast pulses, charges are detonated at different distances x_1^j from the BTD. Numerical pressure gauges around the BTD provide $p_i(t)$ input to the Axelsson BTD model. For the single point methods, an identical setup is used with the BTD replaced by one numerical pressure gauge, located where the center of the BTD would have been.

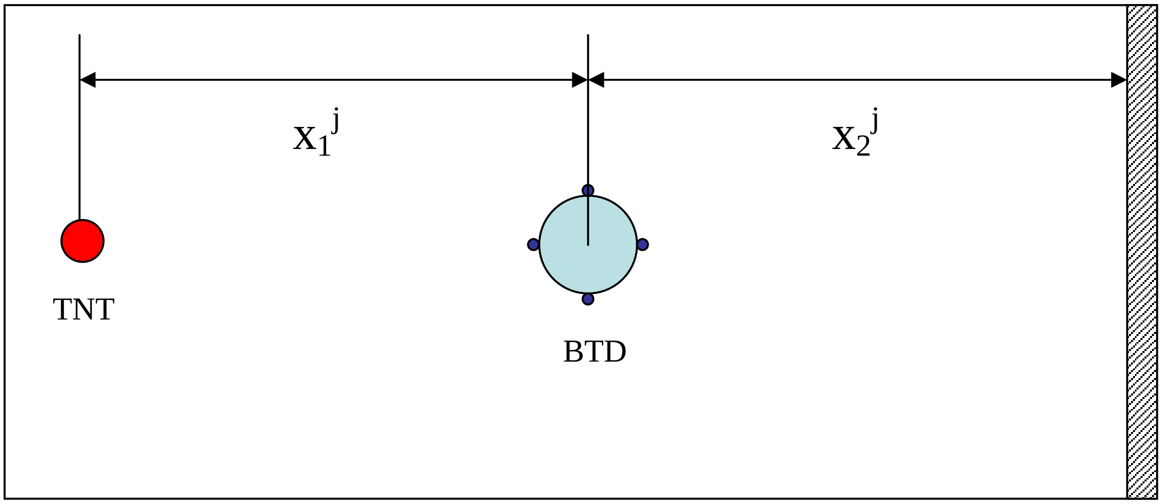


Figure 4: Test setup with BTD, explosive charge on the left and wall on the right

It was the intention to examine a wide variety of relevant scenarios, i.e. different charge sizes at different distances. Partly based on guidelines from STANAG 2280, the following charge scenarios were defined:

- 9 kg TNT (Large briefcase or body borne device)
- 20 kg TNT (Rucksack or suitcase)
- 200 kg TNT (Small car with explosives in the trunk)
- 400 kg TNT (Passenger vehicle)
- 1500 kg TNT (Van)

The most interesting scenarios are those with some chance of injury but where death is not guaranteed. To determine the charge distances for the simulation matrix, pressure data from CONWEP were used together with the lethality model of Bass [2], assuming no reflecting wall. Thus for all charges, two BTD-charge distances were determined: "Case 1: Safe distance" (i.e. threshold for lung injury) and the "Case 2: 50% probability of survival distance". In later simulations a wall was added at various distances x_2^j . The basic simulation matrix is shown in Table 1.

Table 1 Starting position for numerical simulations

Charge weight (j)	x_1^j (safe distance)	x_1^j (50% survivability)
9 kg TNT	5.4 m (110kPa at 5.07ms)	3.4 m (300kPa at 3.50ms)
20 kg TNT	7.4 m (100kPa at 6.85ms)	4.9 m (250kPa at 4.68ms)
200 kg TNT	18.9 m (70kPa at 16.34ms)	12.4 m (170kPa at 11.51ms)
400 kg TNT	24.8 m (65kPa at 20.96ms)	16.6 m (150kPa at 15.58ms)
1500 kg TNT	41.9 m (55kPa at 33.84ms)	26.6 m (140kPa at 25.12ms)

NUMERICAL SIMULATIONS

The following set-ups were compared in the simulations:

- Axelsson BTD (3D-simulation involving a BTD, with four gauges at 90 degrees interval).
- Axelsson SP (3D-simulation without BTD and only a single pressure gauge).
- Modified Weathervane SP (3D-simulation without BTD and only a single pressure gauge.)
- TNO SP (3D-simulation without BTD and only a single pressure gauge).

All numerical simulations were run using ANSYS AUTODYN 12.0 [8]. A subroutine was written implementing the Axelsson model (both BTD and SP) and the Modified Weathervane model in AUTODYN, thus calculating the injury parameters instantly, instead of first running the simulation and then exporting the measured pressure data for processing. For the TNO SP model, the AUTODYN pressure history was exported to an Excel-file for processing.

In all cases, the numerical simulations were run using the following procedure: The detonation and ensuing blast wave propagation was initially spherically symmetric, enabling us to calculate everything in 1D using a grid resolution of 7 mm. The output from this 1D-simulation was then mapped into a coarser Euler Multi-material 3D grid when the situation was no longer spherically symmetric, i.e. when the blast wave reached the BTD. For the 3D-simulations, a graded grid with a resolution of 7 mm around the BTD was used, but a coarser grid further away. The gauge points for the BTD were placed in the Euler grid right outside the BTD.

The air and detonation products were modelled using an Euler Multi-material grid, whereas the BTD was modelled as a rigid boundary on the Euler grid. The standard air and TNT models from the AUTODYN material library were used. Thus, air was modelled as an ideal gas and the TNT was modelled using the JWL-equation.

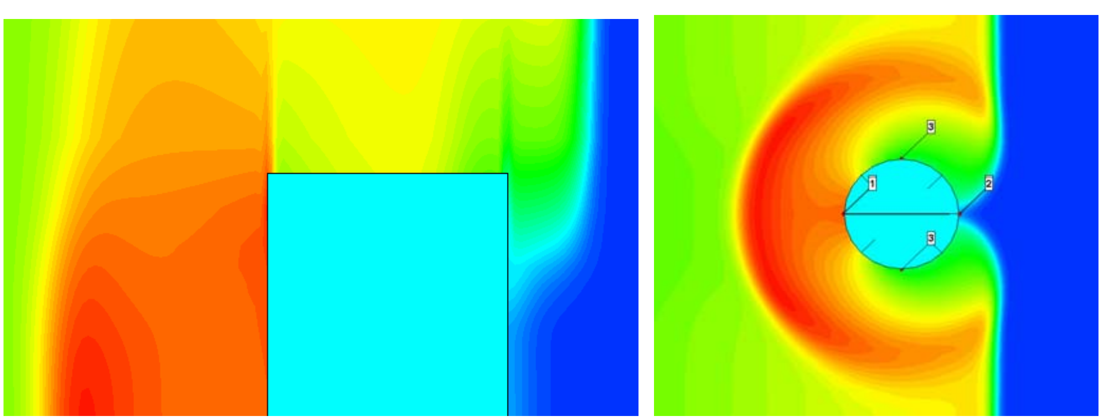


Figure 5: Pressure plots in the 200 kg simulation from two different viewing angles (side and top)

Example pressure plots from the 3D simulations are shown in Figure 5. The gauge locations on the BTD are also indicated.

PRELIMINARY 1D-SIMULATIONS (SAFE DISTANCE)

When no wall or BTD is present, the whole scenario can be modelled using 1D. It is instructive to look at the actual pressures which are generated at the "safe" distance for the various charges. This is shown in Figure 6.

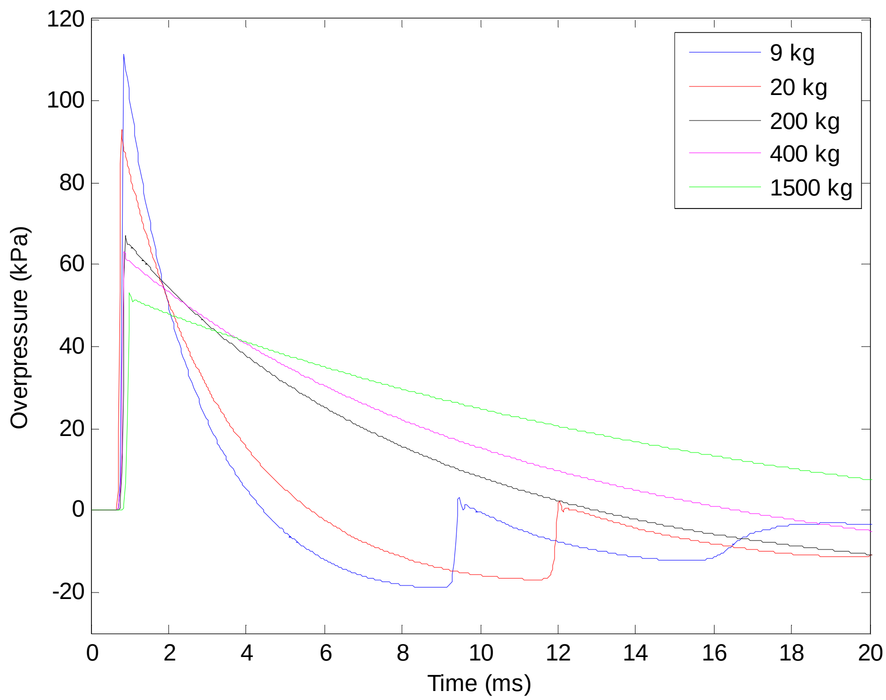


Figure 6: AUTODYN pressure histories at safe distance (according to Bass [2]) for the various charges

As expected, the shape of the pressure pulses are quite different, with the 9 kg pulse having a relatively short duration and high amplitude and the 1500 kg a lower amplitude but longer duration. Also, the pressure amplitude calculated by AUTODYN is very similar to what is predicted by CONWEP (Table 1), thus indicating that our simulations are in accordance with empirical results.

To get an idea of how the solutions of the Axelsson differential equations (1) depend on the pressure input, the Axelsson SP model has been applied to these pressure histories. The results for chest wall velocity are presented in Figure 7.

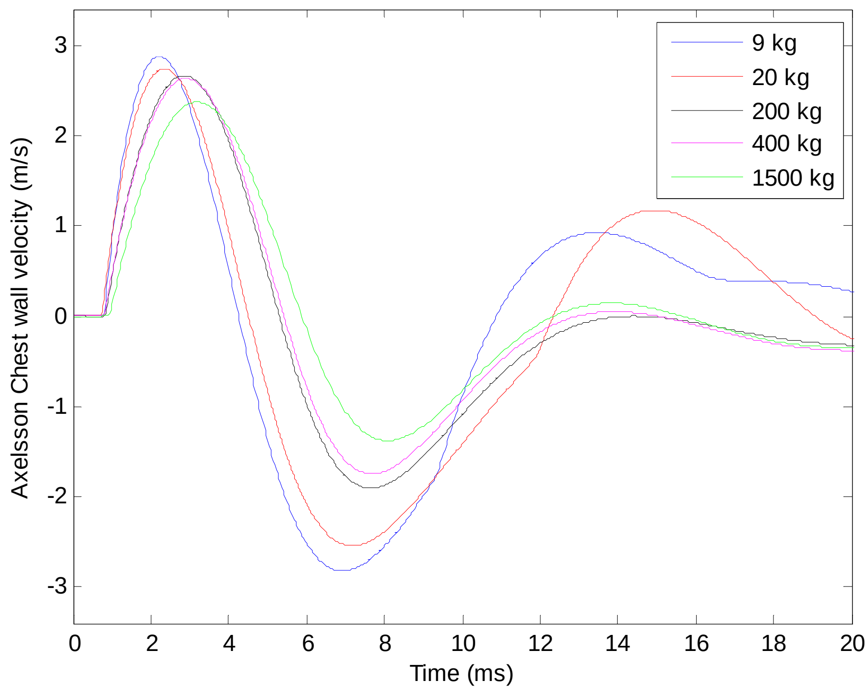


Figure 7: Axelsson SP results for the various 1D pressure histories

We note that in all cases the chest wall velocity has an oscillating form with the maximum velocity being reached for the first peak and the second peak being substantially lower (due to the linear damping term in the Axelsson equation). Despite the large difference in pressure input, the output chest wall velocities show very similar behaviour in the various cases. The duration of the first oscillation seems to increase somewhat with charge size, but not very significantly. The amplitudes of the first pulse (which determines the predicted injury) are also quite similar, which should be expected since the cases were selected exactly with that in mind. Thus, in that respect, Axelsson SP seems to be in good agreement with Bass. However, from a quantitative point of view, it should be noted that in all cases the maximum velocity falls below the Axelsson injury threshold value of 3.6 m/s.

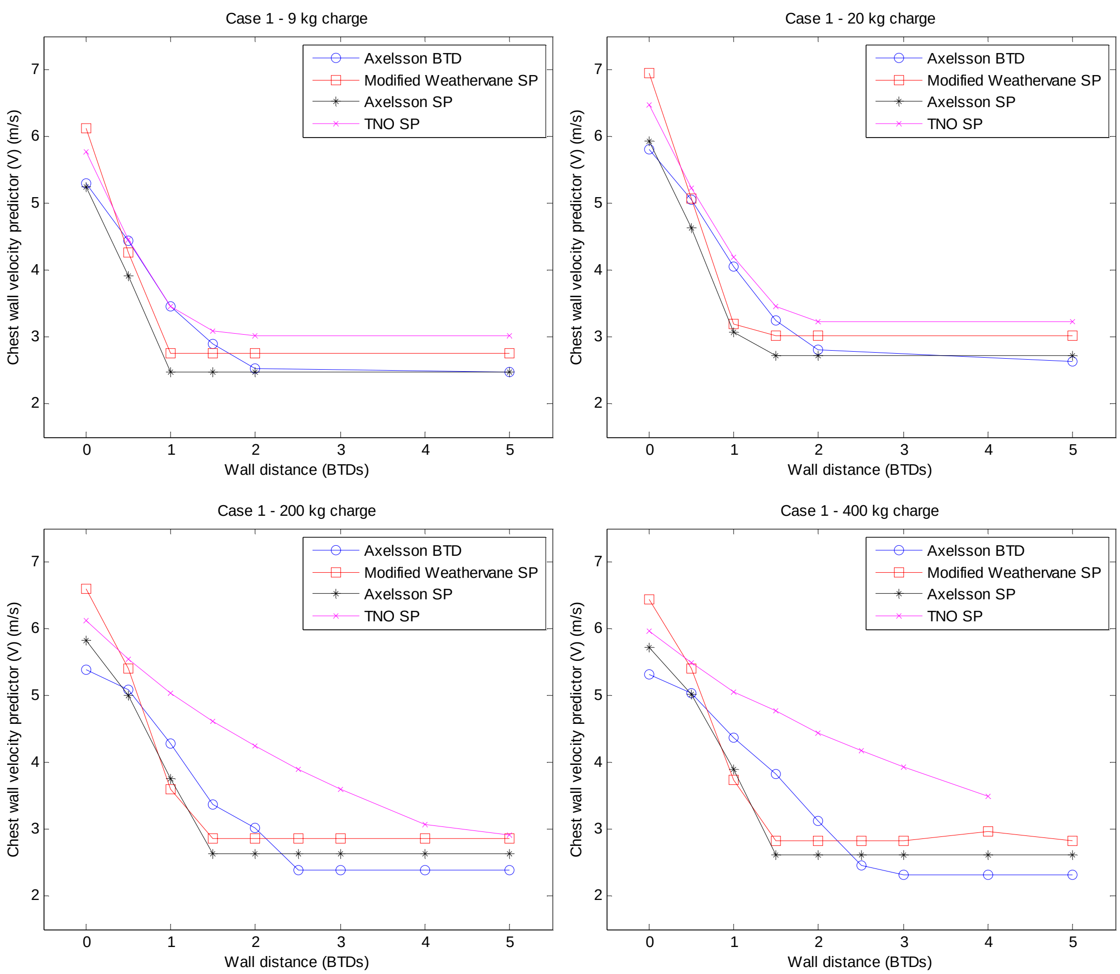
It is also noteworthy that the time for the “chest wall” to complete one “cycle” is not influenced much by the actual loading. Note especially that for 1500 kg the chest wall completes the first cycle long before the positive loading has ended. Thus, since the maximum chest wall velocity in the Axelsson SP model for a single blast wave always occurs on the first positive cycle, the injury calculated will be identical even if the 1500 kg pressure pulse had been suddenly cut off after 6 ms or later.

This property works to our advantage when dealing with blast waves of long duration, since only the first part of the pulse will be required to determine the maximum chest wall velocity. Consequently, it is not always necessary to model the whole blast wave, which reduces the necessary grid size. This property was exploited in the 3D-simulations to reduce computation time.

RESULTS OF 3D-SIMULATIONS

In Figures 8 and 9 we present results for the maximum chest wall velocity, V, as a function of wall distance, calculated by the different methods from pressure data generated by the 3D AUTODYN simulations. The wall distance is measured in number of BTDs (1 BTD = 305 mm).

Case 1: Safe distance (according to Bass)



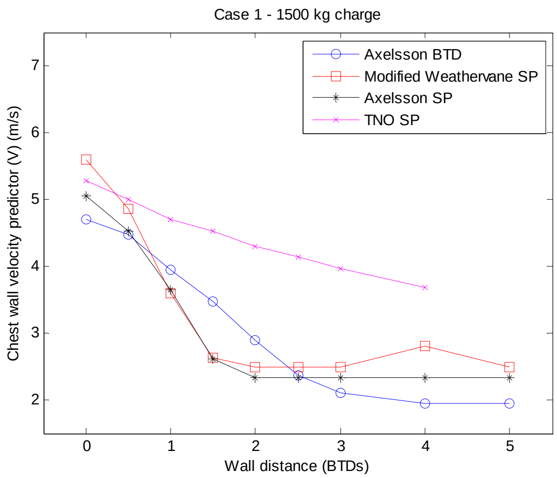
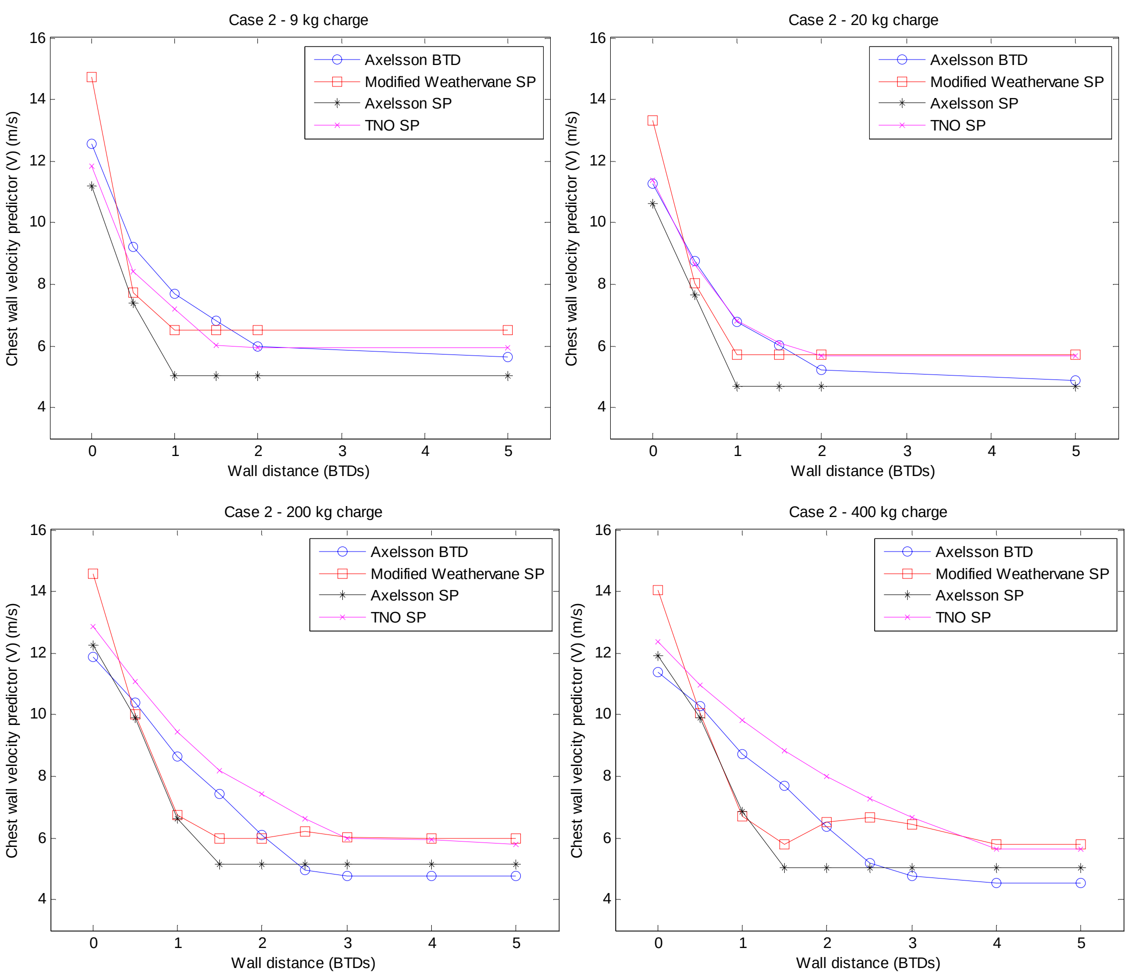


Figure 8: Chest wall velocity predictor (V) for the different approache (Case 1: Safe distance according to Bass), based on 3D AUTODYN simulations

Case 2: 50% survivability distance (according to Bass)



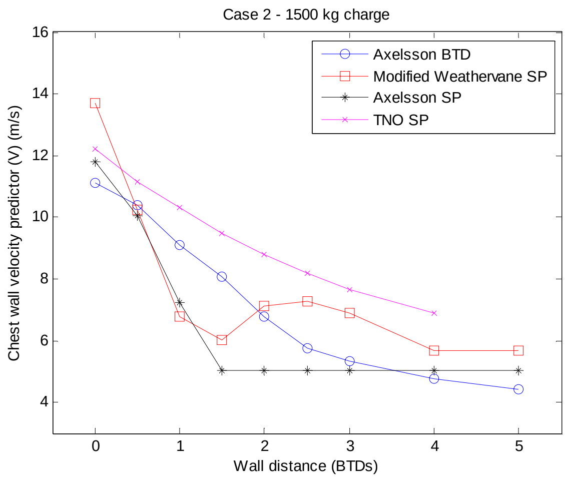


Figure 9: Chest wall velocity predictor for the different approaches (Case 2: 50% survivability according to Bass), based on 3D AUTODYN simulations

DISCUSSION OF 3D-RESULTS

The general impression from the results in Figures 8 and 9 is that all SP models to a large degree provide similar injury estimates to the Axelsson BTD method. This is especially clear when the large uncertainties in the relationship between the Axelsson chest wall velocity *V* and the injury indicator ASII is taken into consideration.

However, a closer inspection of the results reveals some interesting tendencies:

- For the two small charges (9 kg and 20 kg) the correspondence is particularly good for all SP methods independent of wall distance.
- For the larger charges (200 kg, 400 kg and 1500 kg) all SP models are quite accurate when either the wall is very close (0-0.5 BTDs) or far away (> 4 BTDs).
- At intermediate wall distances (around 1-3 BTDs), the methods diverge somewhat. Typically TNO SP will give the highest estimate of *V* while Axelsson SP gives the lowest estimate. TNO SP has roughly the same trend as Axelsson BTD, whereas Axelsson SP quickly decreases to a constant value. Modified Weathervane SP shows an apparently strange behaviour in this regime, especially in the 50% survivability case. The chest wall velocity predictor *V* does not decrease monotonically with wall distance, as one might have expected. After reaching a local minimum, it increases to a local maximum and then falls off again.
- Quantitatively, all models (including Axelsson BTD) predict less injury than Bass [2]. The chest wall velocities should have been 3.6 m/s and 12.8 m/s for lung injury threshold and 50% lethality respectively, to be in agreement. However, these chest wall velocities are only reached when a wall is close behind the BTD, particularly for the 50% survival category, wheras according to Bass this should have happened even without a wall.

To explain the strange tendency of the Modified Weathervane SP, we need to look more closely at how the Axelsson mathematical model works. In Figures 6 and 7 we observe that a typical (one peak) blast wave, produced an oscillating motion of the chest wall. However, because of the damping term in Equation (1), the chest wall motion was attenuated, leading to gradually lower velocity amplitudes for subsequent cycles.

For complex blast waves, i.e. with two or more pressure peaks, the situation can be quite different. Depending on the amplitude and the time difference between the two peaks, the maximum chest wall velocity may occur on the second peak instead of the first. Figure 10 illustrates this situation in the Modified Weathervane case (1500 kg, 50% survivability).

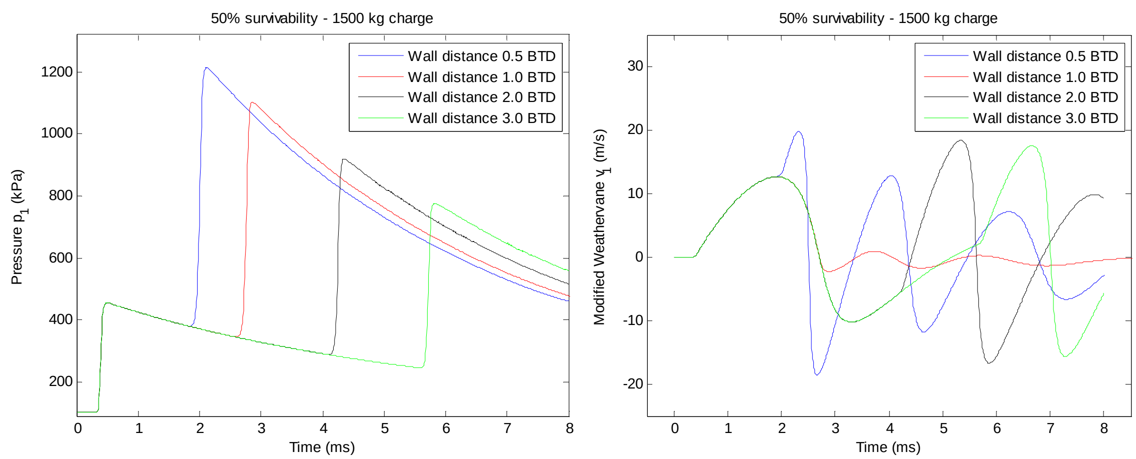


Figure 10: Modified Weathervane chest wall velocity v1(t) for various wall distances

The left plot shows the pressure input $p_1(t)$ (i.e. the reflected pressure from a rigid wall, calculated from the free field pressure, as described earlier) as a function of time with a wall at various distances. As expected, the amplitude of the second peak decreases with wall distance. Intuitively one would therefore expect less injury further away from the wall, but the Axelsson model gives a different result. The right plot shows $v_1(t)$ in Modified Weathervane SP (i.e. sensor assumed to be facing the blast wave) calculated from the pressure input in the left plot.

We see that for 0.5 BTD wall distance, the amplitude of the first velocity peak is increased due to the second pressure peak. However, at a distance of 1.0 BTD, the first cycle has almost been completed and motion is in the negative x-direction ("out-of-phase") when the second wave arrives and therefore it manages only to slow down the chest wall motion. However, if the wall is moved further away (2.0 BTD and 3.0 BTD distance), the second wave arrives on the second velocity cycle ("in phase") and increases the chest wall velocity amplitude to a higher value than for the first cycle. This "phase effect" explains the strange tendency of the Modified Weathervane SP model mentioned above.

One might have expected a similar effect for Axelsson SP, but this did not happen in any of our cases. An explanation is given in Figure 11, which shows the chest wall velocity output from Axelsson SP with the corresponding pressure input. (Note that the Axelsson

chest wall velocity is equal to the two components $v_2=v_3(t)$ in Modified Weathervane SP.)

On comparing the duration of one chest wall cycle in Modified Weathervane SP (Figure 10) and Axelsson SP (Figure 11), we note that it is longer for Axelsson SP. This feature, which is due to the higher pressure amplitude in the Modified Weathervane SP, will explain the different behaviour of Axelsson SP.

As expected, for 0.5 BTD wall distance, the amplitude of the first velocity peak is increased due to the second pressure peak. But, due to the longer duration of one chest wall cycle in Axelsson SP, at wall distance of 1.0 BTD and larger the results differ from Modified Weathervane SP. For 1.0 BTD distance, the second pressure peak arrives while the chest wall velocity is still near the local maximum and manages to push it slightly higher, but not higher than the velocity peak at 0.5 BTD. At a distance of 2.0 BTD the Axelsson SP gives roughly the same "out-of- phase" situation as was seen at 1.0 BTD for $v_1(t)$ in Modified Weathervane, where the second pressure peak only manages to slow down the chest wall motion. At distances larger than this (only 3.0 BTD is illustrated), the second pressure peak is again "in phase" with the chest wall motion, but then the wall is so far away that the pressure amplitude has fallen too much to enable the second velocity peak to go above the first peak.

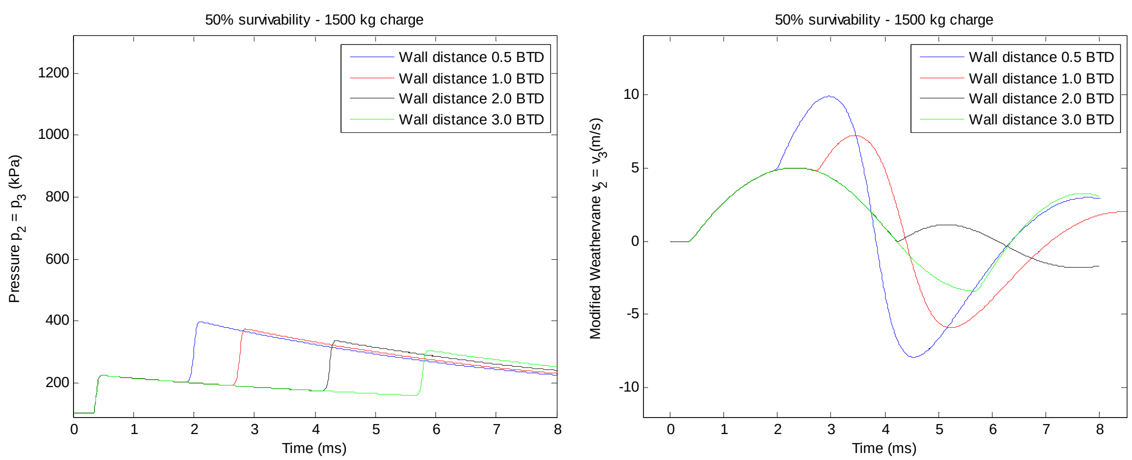


Figure 11: Modified Weathervane chest wall velocity v2=v3(t) for wall at various distances (equal to the Axelsson SP chest wall velocity)

As the phase effect is a feature of the Axelsson model itself, it will also happen in the Axelsson BTD model. However, it will not manifest itself so obviously in the chest wall velocity since Axelsson BTD depends on four different pressure signals (which are all different from the single point pressure pulse). Typically one signal will be out-of-phase and another in-phase, thus compensating for each other and diluting the phase effect.

Notice that it is the out-of-phase effect which causes Axelsson SP and Modified Weathervane SP to have a different trend than Axelsson BTD. The out-of-phase effect happens for all charges and it manifests itself more or less when the wall is at distances around 0.5-2 BTD by underestimating the BTD chest wall velocity. If these data points (0.5-2 BTD) were ignored, a much better correspondence with the Axelsson BTD would have been obtained.

An obvious question is whether the “out-of-phase effect” actually is a real physical effect. The current results with the Axelsson BTD-model suggests it does not manifest itself in the injury levels. In the TNO SP model (see [6]), the out-of-phase effect is deliberately ignored to be on the safe side, resulting in higher injury predictions in the intermediate regime (1-3 BTDs wall distance) than for the other SP models. If desirable, the TNO SP model could, in principle, be tuned to make it quantitatively in better agreement with the Axelsson BTD model.

RESULTS FOR INDIVIDUAL GAUGES IN MODIFIED WEATHERVANE SP

Having seen that Modified Weathervane SP gives reasonable estimates of the Axelsson BTD chest wall velocity predictor *V*, the predictions for each individual gauge are studied as well. The idea behind the Weathervane method is, of course, to predict what would have been measured on a BTD if it had been present. As an example, we look at the 1500 kg “50% survivability” case and compare individual gauge results for Axelsson BTD and Modified Weathervane SP. This is illustrated in Figure 12.

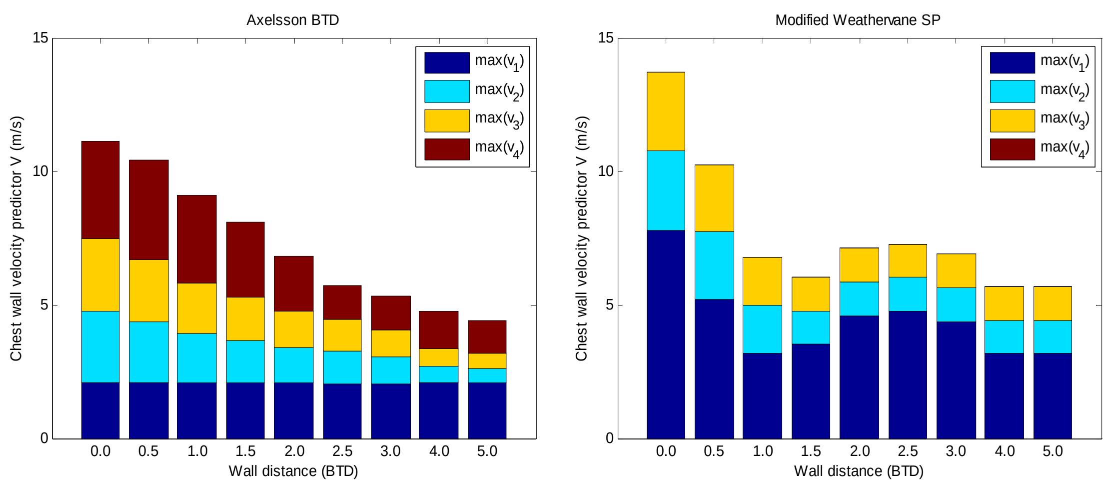


Figure 12: Comparison of results from Axelsson BTD and Modified Weathervane SP for individual gauges

We note that the correspondence between the two methods is not very good at all for the individual gauges. Modified Weathervane SP produces much too high results for the front gauge, particularly when there is a wall present. (The original Weathervane model will do slightly better by producing lower results). Note that the front gauge of Axelsson BTD gives almost a constant value as it sees a relatively weak second peak because of shielding by the BTD itself. In an SP model, obviously there can be no such effect. This shows clearly that it is the second peak which causes the high velocity v_1 in the Weathervane SP model.

The assumption in the Weathervane model of ambient pressure behind the BTD is also clearly not correct. In fact, the maximum chest wall velocity from the Axelsson BTD rear sensor is seen to be almost consistently higher than from any of the side sensors. This is natural when a wall is present, since the pressure becomes very high when the

shock is reflected from the wall and then reflected at the rear end of the BTD again. However, even without a wall, the rear sensor makes a non-negligible contribution.

Fortunately, as we see, the errors to a large degree cancel each other out, leading to a reasonable estimate for the chest wall velocity predictor *V*. Only the out-of-phase effect, which is obvious here too, is not cancelled out. Results from other charge weights are similar.

CONCLUSIONS

Numerical simulations comparing various single point (SP) approaches with the Axelsson BTD method have been performed. A variety of relevant cases were examined, ranging from small charges at a short distance to large charges far away, for both free field situations and complex blast (by the presence of a wall behind the target).

Generally the single point methods gave quite good results for the Axelsson BTD chest wall velocity predictor *V*. This was perhaps not surprising for the Weathervane method which was designed explicitly with this in mind. However, it is interesting to note that the (simpler) Axelsson SP and TNO SP methods seem to perform equally well.

Particularly for small charges there was very good agreement between the various methods. For large charges the agreement was good close to the wall and far away from the wall. In an intermediate regime (1-3 BTDs wall distance) we saw that the SP models diverged somewhat. This was traced back to a "phase effect" in the Axelsson mathematical model. The TNO SP method seemed to overestimate the injury in this regime, which was due to a deliberately chosen deviation from the Axelsson model, in order to avoid a possible underestimation of injury, as was observed for the Modified Weathervane SP and Axelsson SP methods.

The results for individual gauges in the Modified Weathervane SP model were also examined and the results were not promising compared with Axelsson BTD. In fact, the reflected pressure assumption for the front sensor was seen to consistently give much too high chest wall velocities (the regular Weathervane will be slightly better here). The assumption of ambient pressure for the rear sensor is incorrect, even without a wall, and the pressure at the side gauges is always lower than the free field pressure. With a wall present, these individual gauge predictions become even worse. However, it is interesting that the errors in general seem to "cancel each other out" so that the total chest wall velocity predictor is reasonable, even with a wall present.

To improve the physics in the (modified) Weathervane model, an option would be to find a different method of calculating for the individual gauges when a wall is present. However, currently this is not thought worth the effort since, for all practical purposes, the available single point models produce good enough results. This has been demonstrated for such a large variety of cases in this paper, that we believe that it is unlikely there will be a relevant case where the models deviate significantly. With the large uncertainty in the Axelsson BTD model itself, developing more advanced models to estimate it more accurately is probably not the way to go.

We have not adressed the topic of whether Axelsson BTD actually gives correct injury predictions, except for the observation that it predicts less lethality than Bass. Our focus was on whether the various simpler SP approaches were able to approximate the Axelsson BTD model. Since the Axelsson BTD method itself must be considered as an approximation method, which has not been validated for any of our case studies, an approximate agreement has been considered as sufficient. When the Axelsson BTD model gives reasonable predictions, either of the SP approaches will usually give acceptable results. For the analysis of a specific scenario, knowledge about how the different SP models behave, should help in assessing the situation. For example, the TNO SP method will most likely give the highest injury estimate and may be preferred for use if one wants to be particularly careful.

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